MiniBooNE and the SNS

Overview of MiniBooNE & Current Status
Neutrino Physics in a Post-MiniBooNE Era

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Outline

- LSND : The motivation for MiniBooNE
- MiniBooNE Summary
- The SNS
  - ⇒Properties of the neutrino beam
  - ⇒Proposed detectors
  - ⇒Interactions of neutrinos in the detectors
  - ⇒How to use these interactions to test neutrino physics models

Neutrino Oscillations

Δm^2 is the mass squared difference between the two neutrino states

Distance from point of creation of neutrino beam to detection point

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\, \Delta m^2 L}{E}\right)$$

θ Is the mixing angle

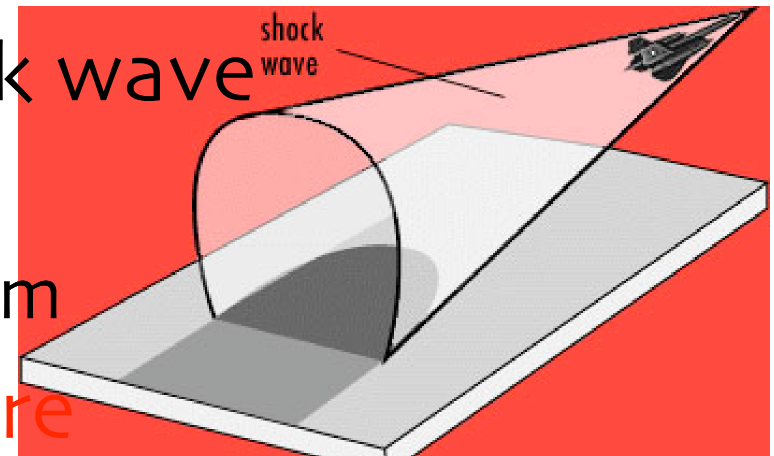
E is the energy of the neutrino beam

Observing ν Interactions

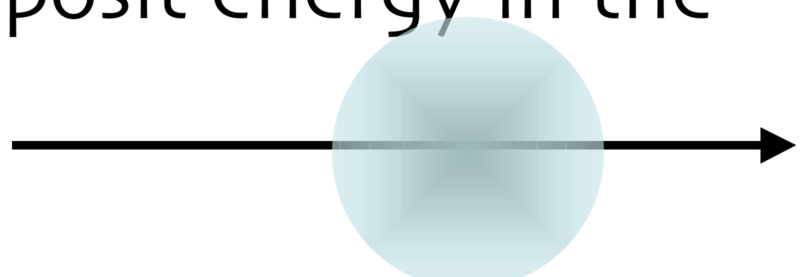
- Don't look directly for neutrinos
- Look for products of neutrino interactions
- Passage of charged particles through matter leaves a distinct mark
  - ⇒Cerenkov effect / light
  - ⇒Scintillation light

Cerenkov and Scintillation Light

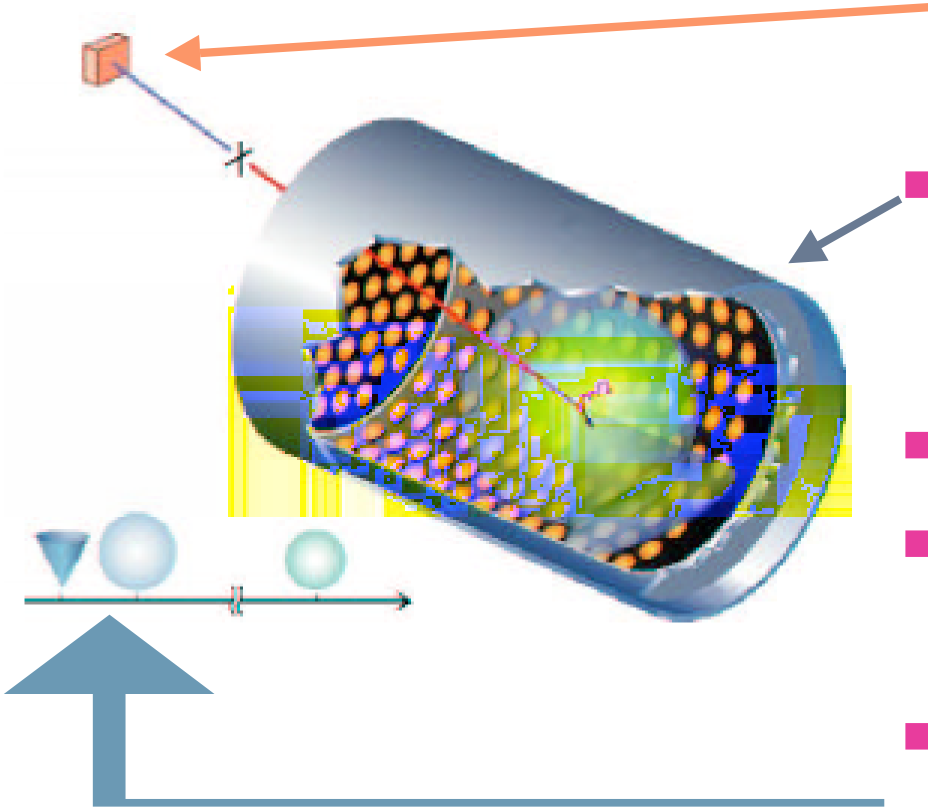
- Charged particles with a velocity greater than the speed of light * in the medium* produce an E-M shock wave
  - $\Rightarrow$ v > 1/n
  - $\Rightarrow$Similar to a sonic boom
- Prompt light signature



- Charged particles deposit energy in the medium
- Isotropic, delayed



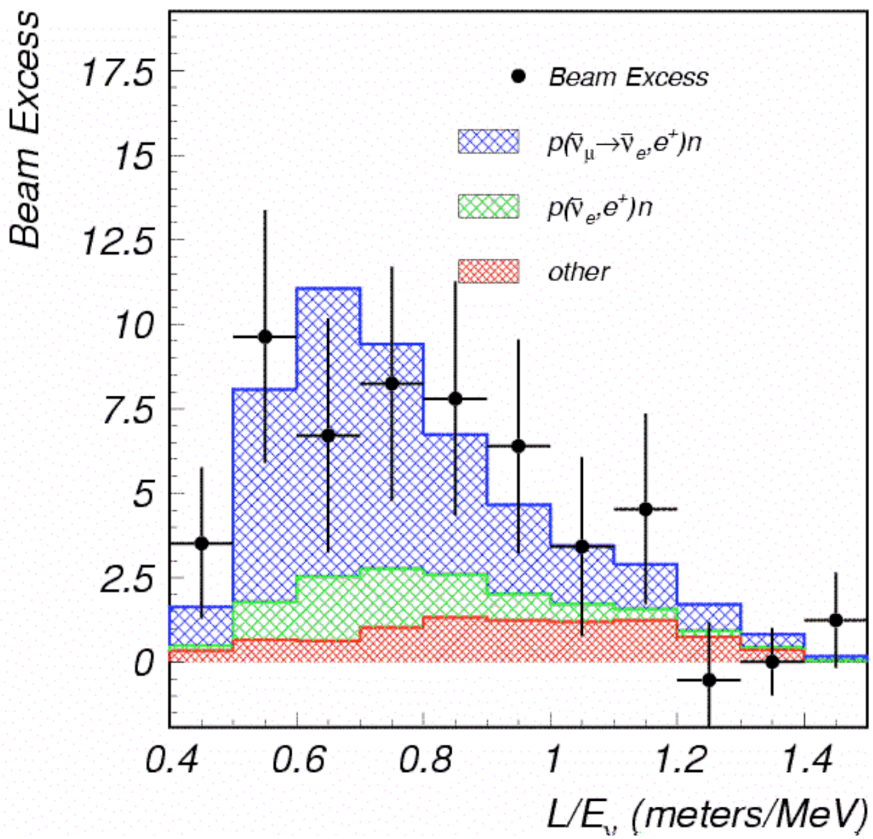
The (In)famous LSND



- 800 MeV proton beam + H_2O target, Copper beam stop
- 167 ton tank, liquid scintillator, 25% PMT coverage
- E_ν ~20-50 MeV
- L ~25-35 meters
- $\bar{\nu}_e + p \rightarrow e^+ + n$

  $\Rightarrow n + p \rightarrow d + \gamma$ (2.2 MeV)

The LSND Result

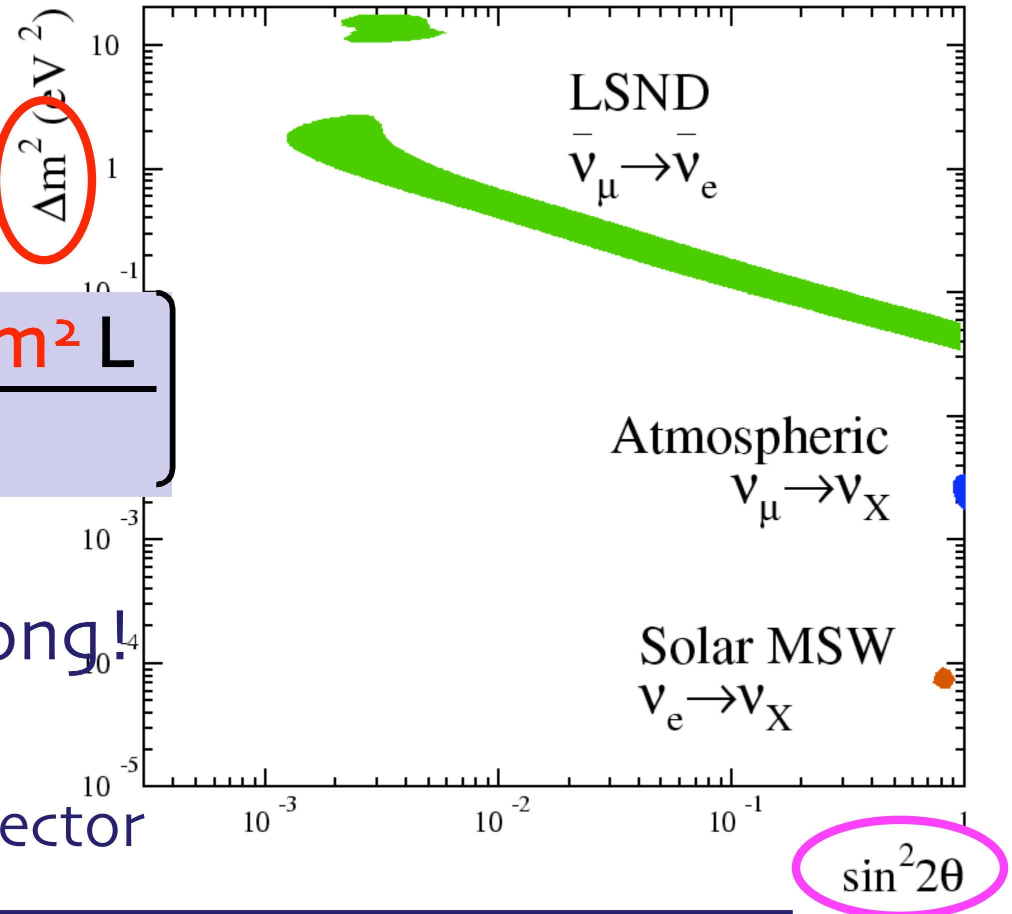


- Different from other oscillation signals
- Higher Δm^2
- Smaller mixing angle
- Much smaller probability (very small signal) ~0.3%

The LSND Problem

$$\Delta m^2_{ab} = m_a^2 - m_b^2$$

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\, L}{E}\right)$$



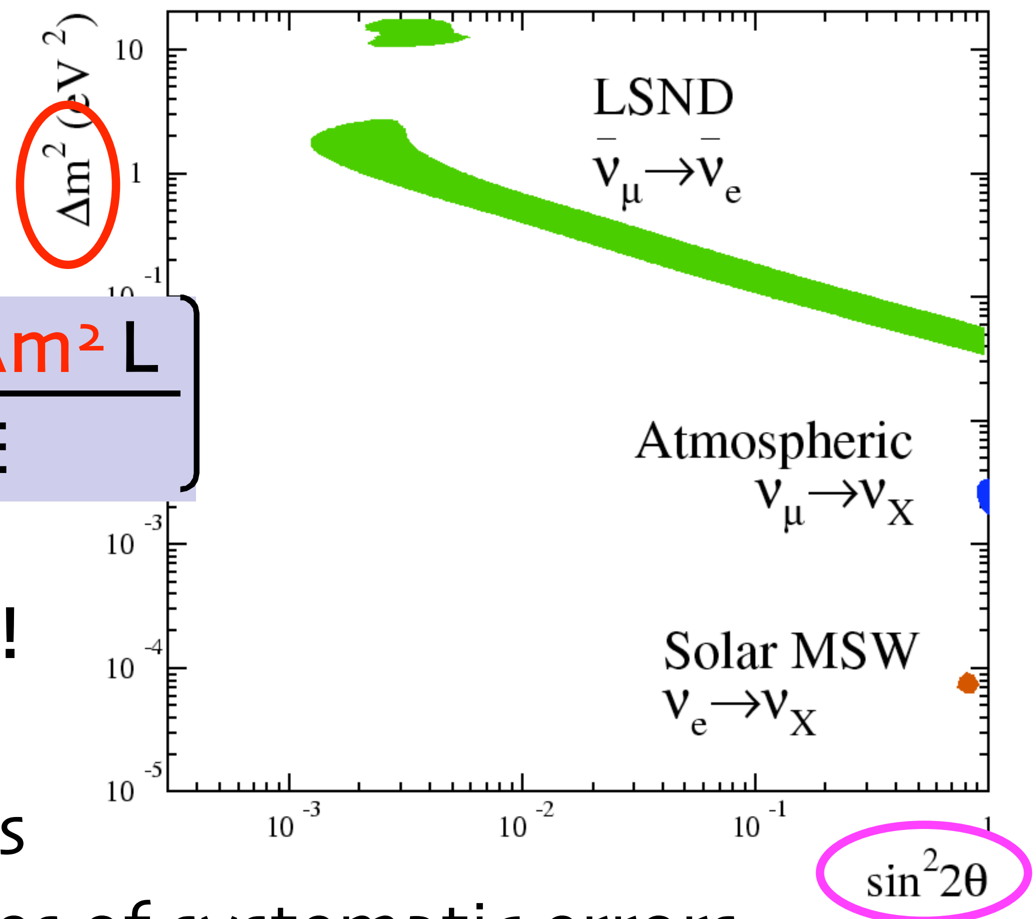
- Something must be wrong!
  - ⇒Flux calculation
  - ⇒Measurement in the detector
  - ⇒Both
  - ⇒Neither

Reminiscent of the great Ray Davis Homestake missing solar neutrino problem!

Confirming LSND

$$\Delta m^2_{ab} = m_a^2 - m_b^2$$

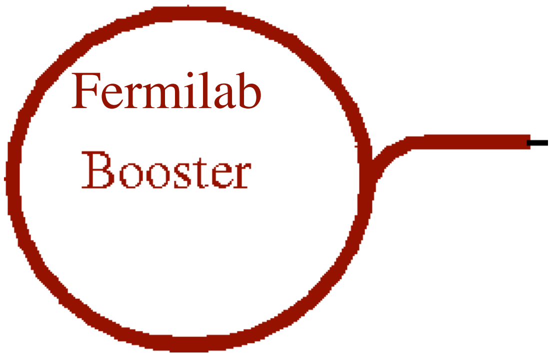
$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\, L}{E}\right)$$



- Need precision expt!
- Want the same L/E
- Want higher statistics
- Want different sources of systematic errors
- Want different signal signature and backgrounds

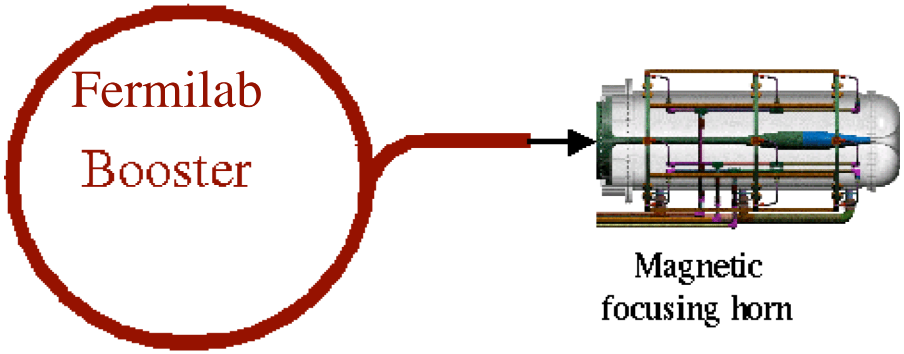
MiniBooNE

MiniBooNE Neutrino Beam



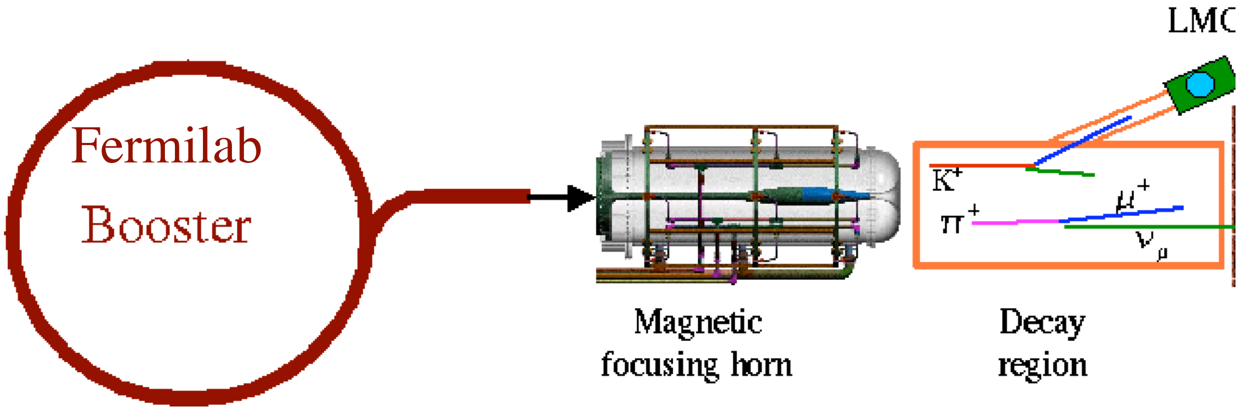
- Start with an 8 GeV beam of protons from the booster

MiniBooNE Neutrino Beam



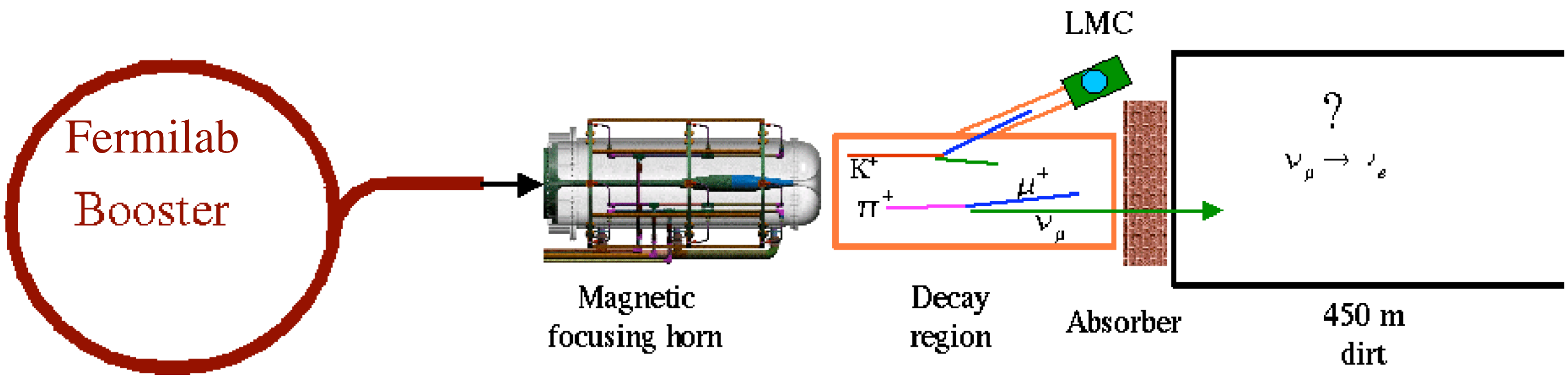
- The proton beam enters the magnetic horn where it interacts with a Beryllium target
- Focusing horn allows us to run in neutrino, anti-neutrino mode
  - ⇒Collected ~6×10^{20} POT, ~600,000 ν events
  - ⇒Running in anti-ν mode now, collected ~1×10^{20} POT

MiniBooNE Neutrino Beam



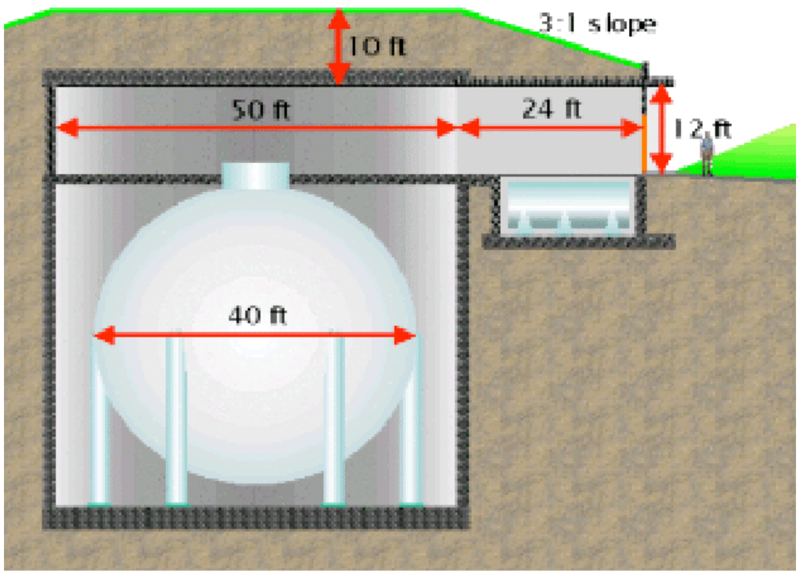
- p + Be = stream of mesons (π, K)
- Mesons decay into the neutrino beam seen by the detector
  - $\Rightarrow K^+ / \pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

MiniBooNE Neutrino Beam

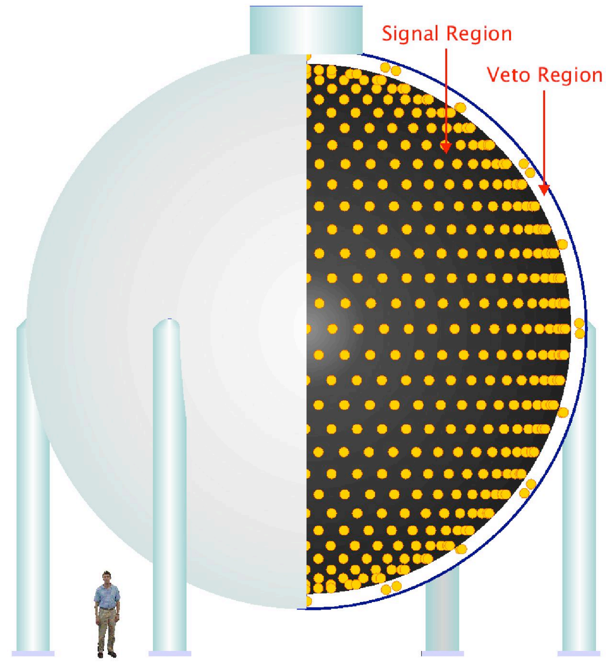


- An absorber is in place to stop muons and un-decayed mesons
- Neutrino beam travels through 450 m of dirt absorber before arriving at the MiniBooNE detector

MiniBooNE Detector

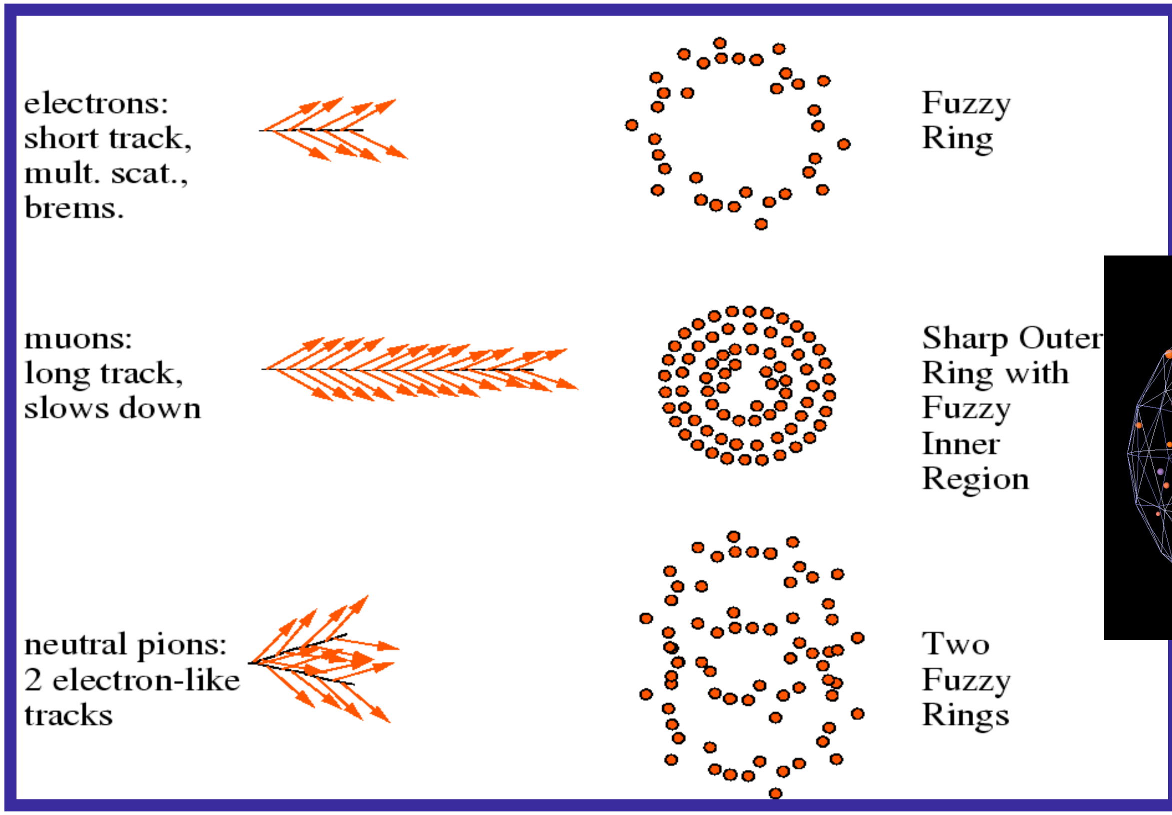


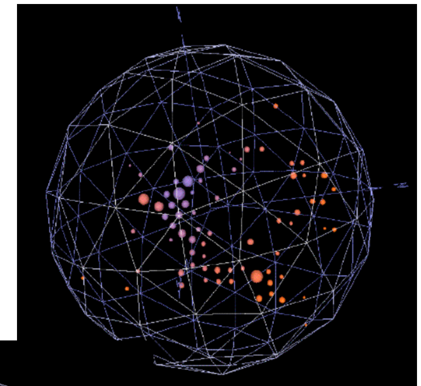
Detector

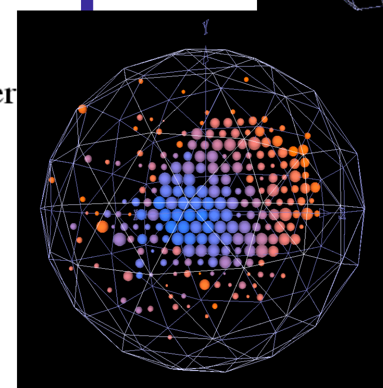


- 12.2 meter diameter sphere
- Pure mineral oil
- 2 regions
  - ⇒Inner light-tight region, 1280 PMTs (10% coverage)
  - ⇒Optically isolated outer veto-region, 240 PMTs

Event Signature







MiniBooNE Current Status

- MiniBooNE is performing a blind analysis (closed box)
  - ⇒Some of the info in all of the data
  - ⇒All of the info in some of the data
  - ⇒~~All of the info in all of the data~~

We haven't yet opened the box

Final Outcomes

Confirm LSND	Inconclusive	Reject LSND

Final Outcomes

Confirm LSND

Inconclusive

Reject LSND

Need to determine what causes oscillations

Final Outcomes

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Need to collect more data / perform a new experiment

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Final Outcomes

Confirm LSND

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All Roads Lead to the SNS

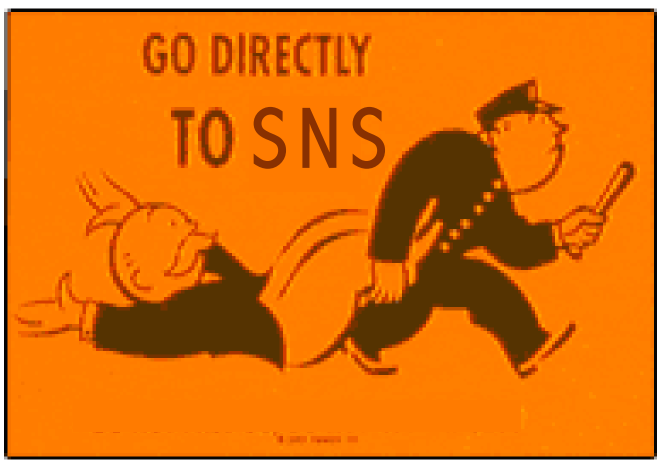
Confirm LSND

Need to determine what causes oscillations

Inconclusive

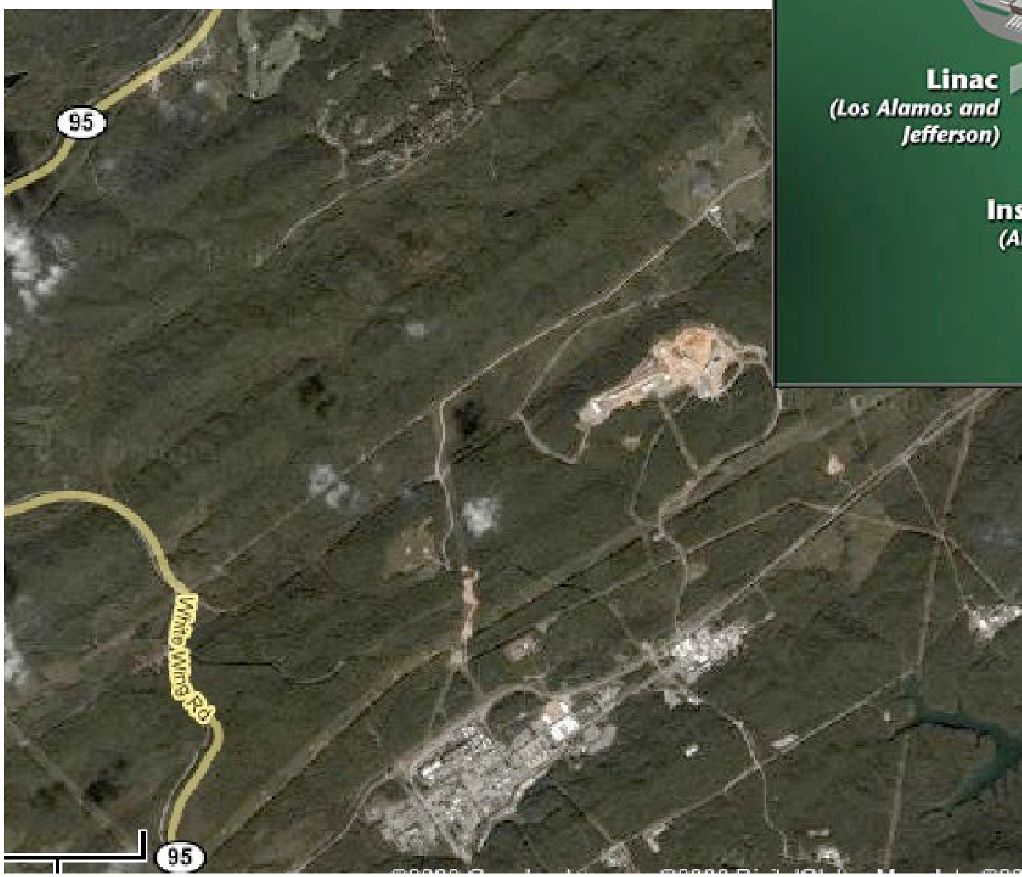
Need to collect more data / perform a new experiment

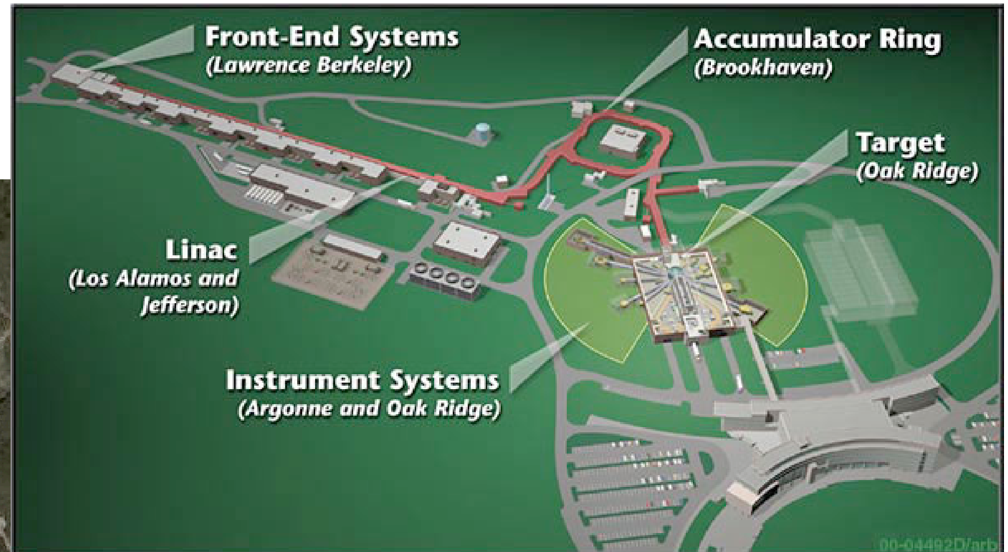
Reject LSND



What is the SNS?

Spallation Neutron Source





Accelerator based neutron source in Oak Ridge, TN

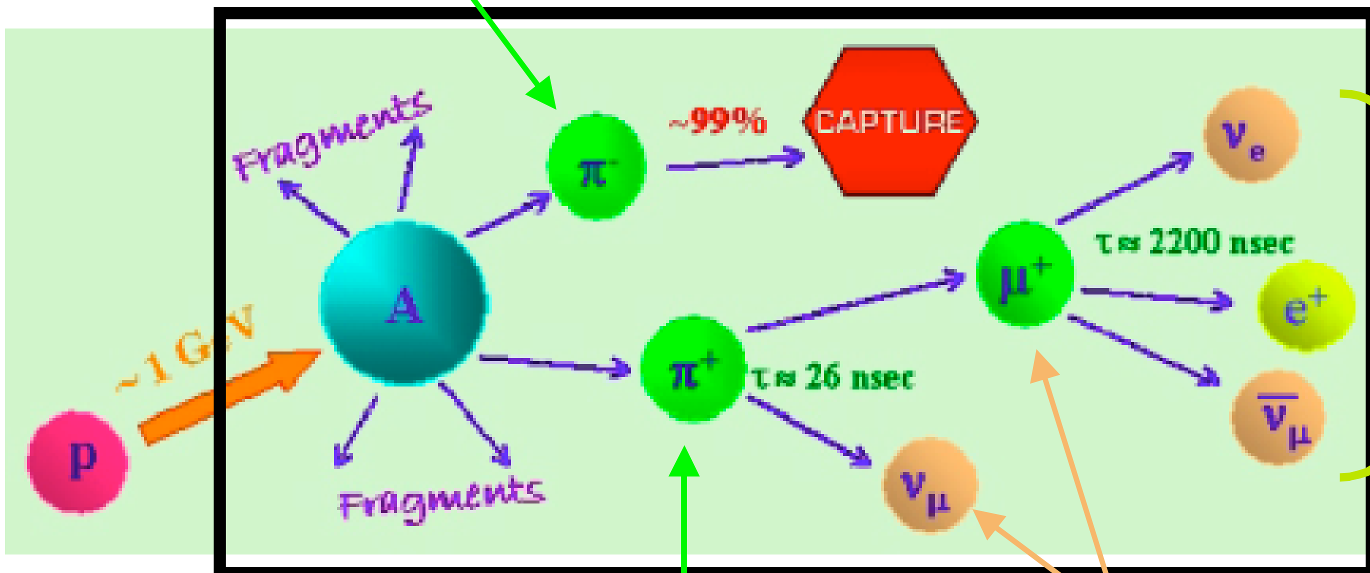
The Spallation Neutron Source

- Pulsed bunches of 1 GeV protons sent into liquid mercury target 60 times/second
- Pulses 695 ns wide (LAMPF = 600 μs wide, FNAL = 2000 ns wide)

- Neutrons freed by the spallation process are collected and guided through beam lines to various experiments
- Neutrinos come for free

The Spallation Neutron Source

π^- absorbed by target



E range up to 52.8 MeV

Target Area

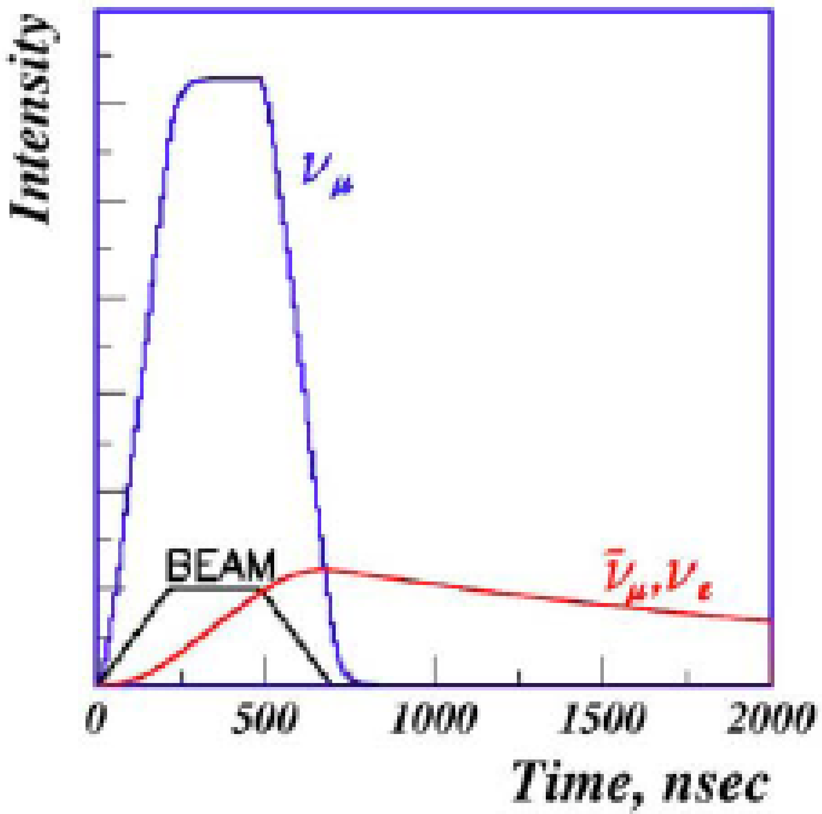
π^+DAR

Mono-Energetic!
ν_μ= 29.8 MeV

(Liquid Mercury (Hg+) target)

The Spallation Neutron Source

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\Rightarrow \tau$ = 26 ns
- $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$
  - $\Rightarrow \tau$ = 2.2 μs



- Pulse timing, beam width, lifetime of particles = excellent separation of neutrino types

The Spallation Neutron Source

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
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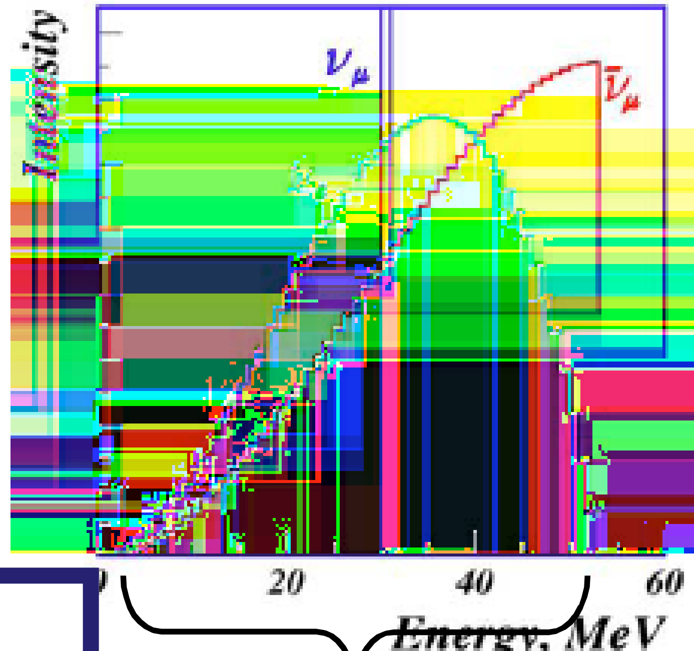
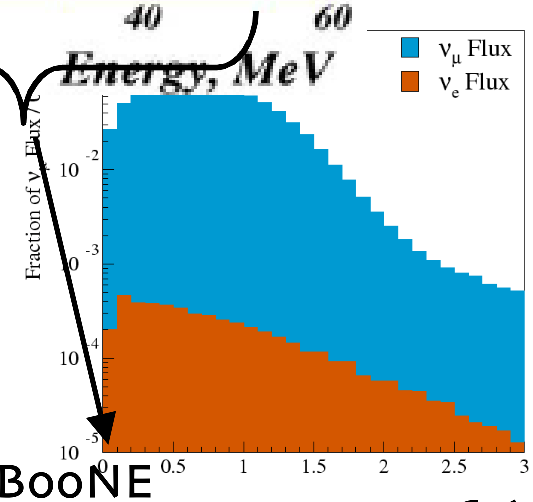
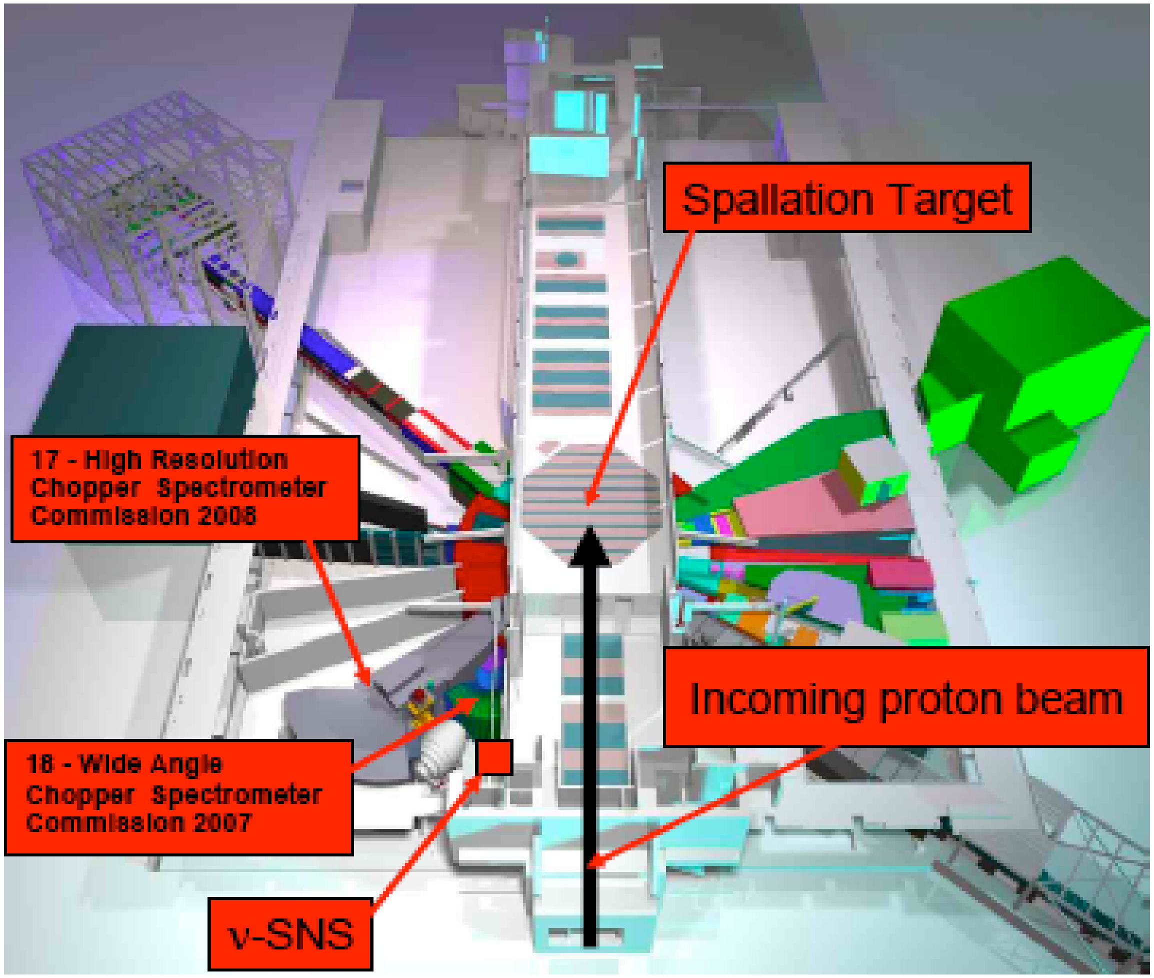


- Mono-energetic ν_μ
  - $\Rightarrow$ E = 29.8 MeV
- $\overline{\nu}_\mu$, ν_e = known distributions
  - $\Rightarrow$ end-point E = 52.8 MeV

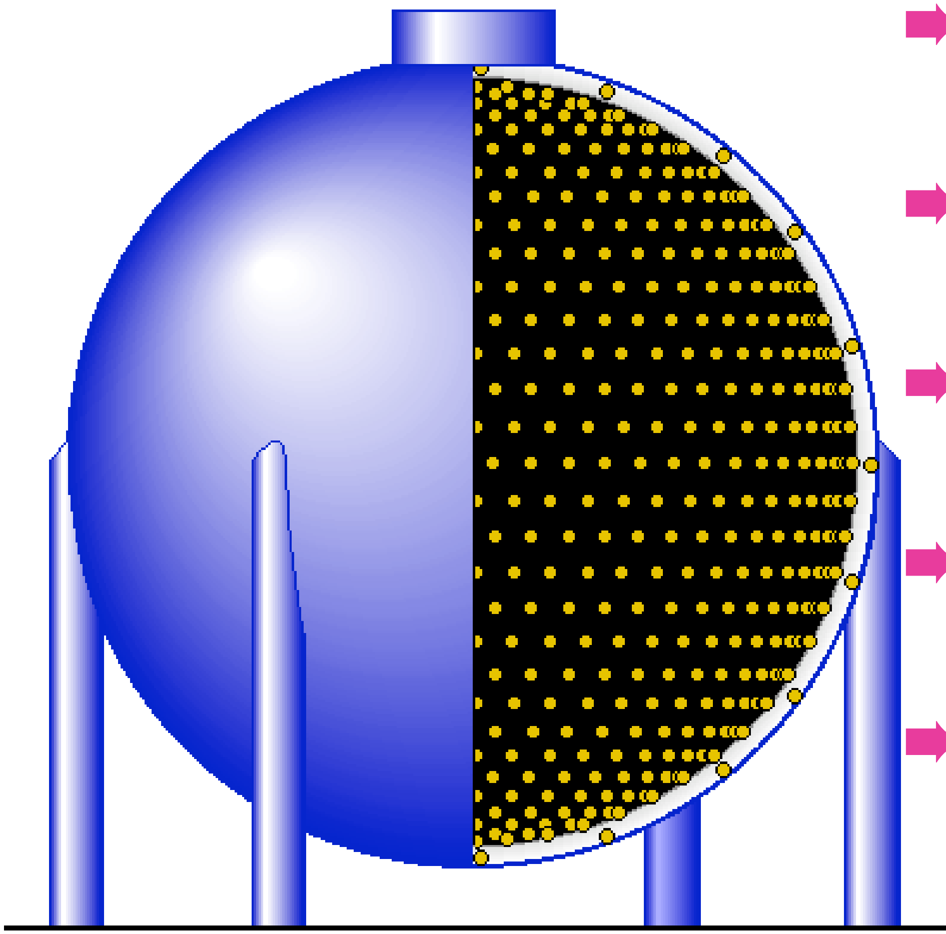


SNS Near Detectors

- 2 near detectors
  - ⇒ Mini-MiniBooNE
  - ⇒ Segemented Detector
- 2004 : LOI submitted to Oak Ridge
- August 2005 : proposal submitted to DOE
- Status : awaiting funding



SNS Far Detector



- MiniBooNE/LSND-type detector
- Higher PMT coverage (25% vs 10%)
- Mineral oil + scintillator (vs pure oil)
- Faster electronics (200 MHz vs 25 MHz)
- ~60m upstream of the beam dump/target
  - ⇒Removes DIF bgd

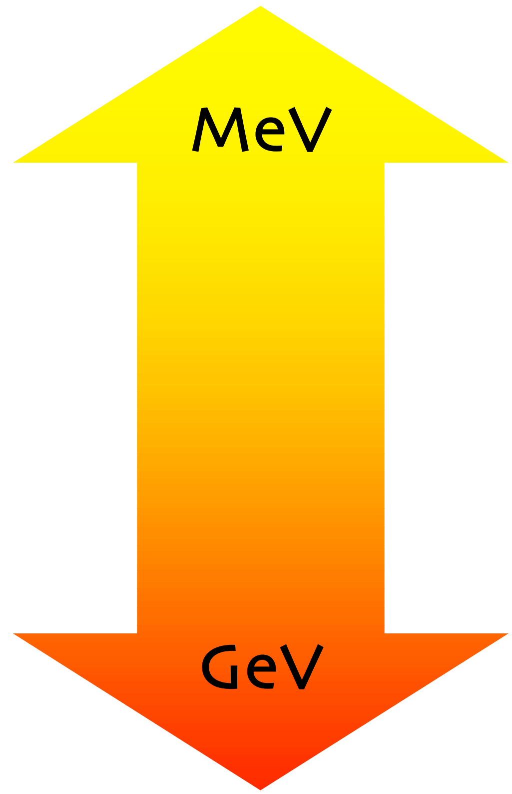
Neutrino Interactions

Elastic Scattering

Quasi-Elastic Scattering

Single Pion Production

Deep Inelastic Scattering



Neutrino Interactions

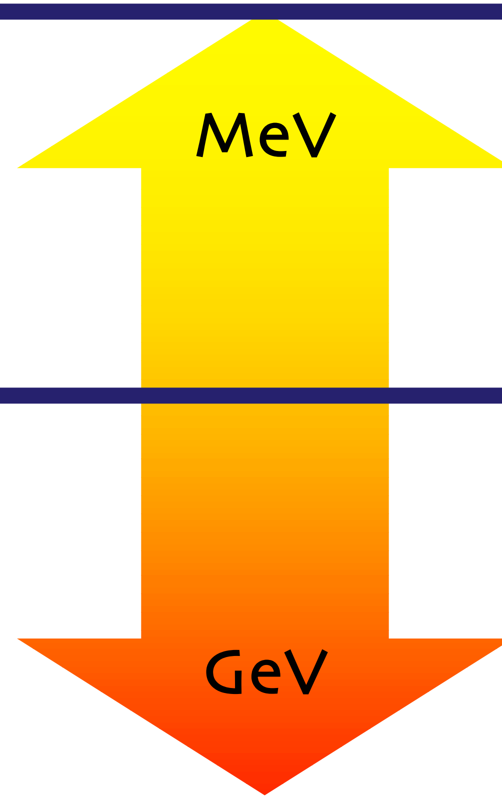
SNS Allowed Interactions

Elastic Scattering

Quasi-Elastic Scattering

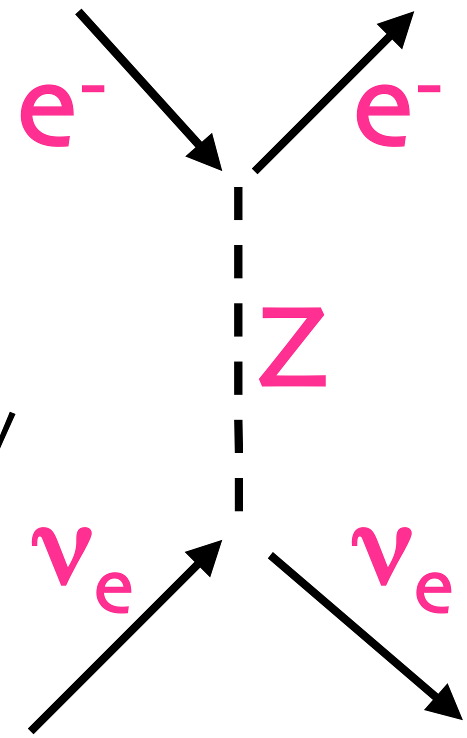
Single Pion Production

Deep Inelastic Scattering



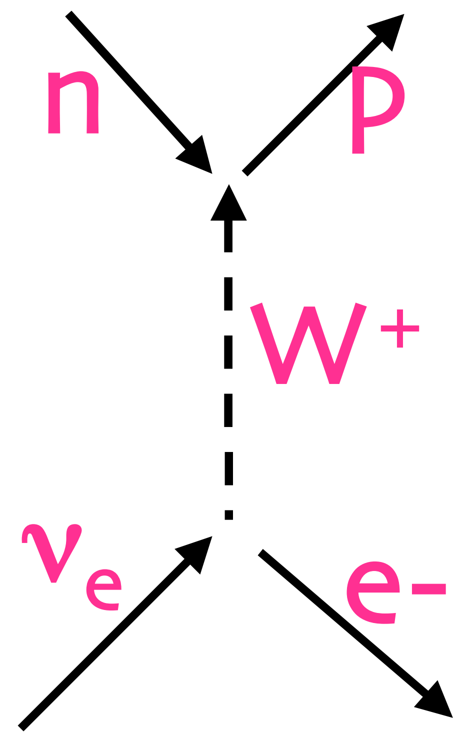
Elastic Scattering

- Target left intact
- Neutrinos can elastic scatter from any particle (electrons, protons)
- Neutrino imparts recoil energy to target = how we observe these interactions



Quasi-elastic Scattering

- Neutrino in, charged lepton out
- Target changes type
- Need to conserve electric charge at every vertex
- Need minimum neutrino E
  - ⇒ Need enough CM energy to make the two outgoing particles



Neutrino Interactions @ SNS

- All neutrinos produced from a ***Decay At Rest*** source
- All neutrino types may engage in NC interactions
- Muon mass = 105 MeV, Electron mass = 0.511 MeV
  - ⇒Muon neutrinos do not have a high enough energy at the SNS to engage in CC interactions!

How do we use these interactions to search for new physics?

ν_μ and anti-ν_μ Osc. Searches

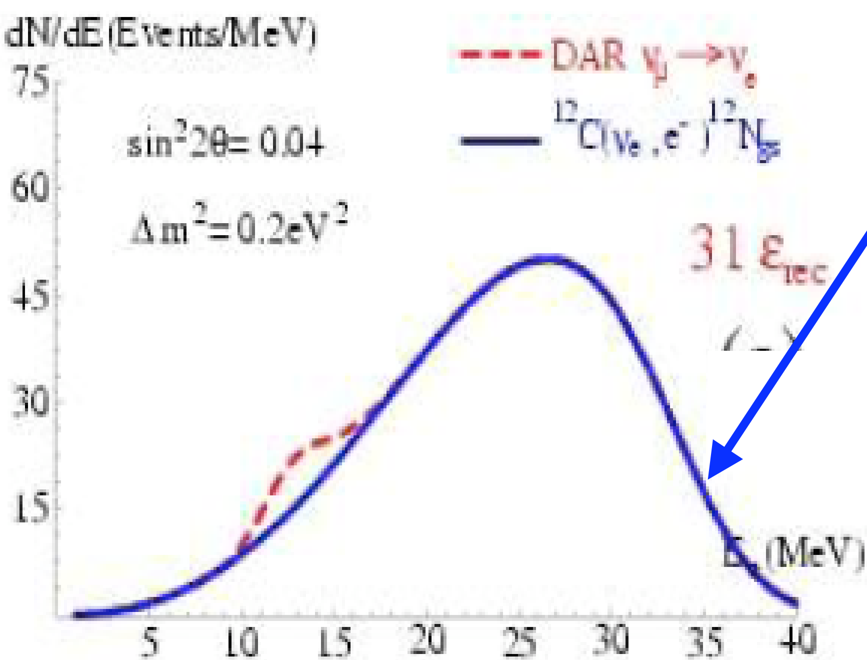
- 2 oscillation searches at SNS can be performed with CC interactions to look for flavor change
- Appearance : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (ala LSND)
  - $\Rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$
  - $\Rightarrow n + p \rightarrow d +$ 2.2 MeV photon
- Appearance : $\nu_\mu \rightarrow \nu_e$
  - $\Rightarrow \nu_e + {}^{12}C \rightarrow e^- + {}^{12}N_{gs}$
  - $\Rightarrow {}^{12}N_{gs} \rightarrow {}^{12}C + e^+$ (~8 MeV) $+ \nu_e$
  - $\Rightarrow$MiniBooNE uses $\nu_e + n \rightarrow e^- + p$

lower E ν_e
vs
higher E ν_e

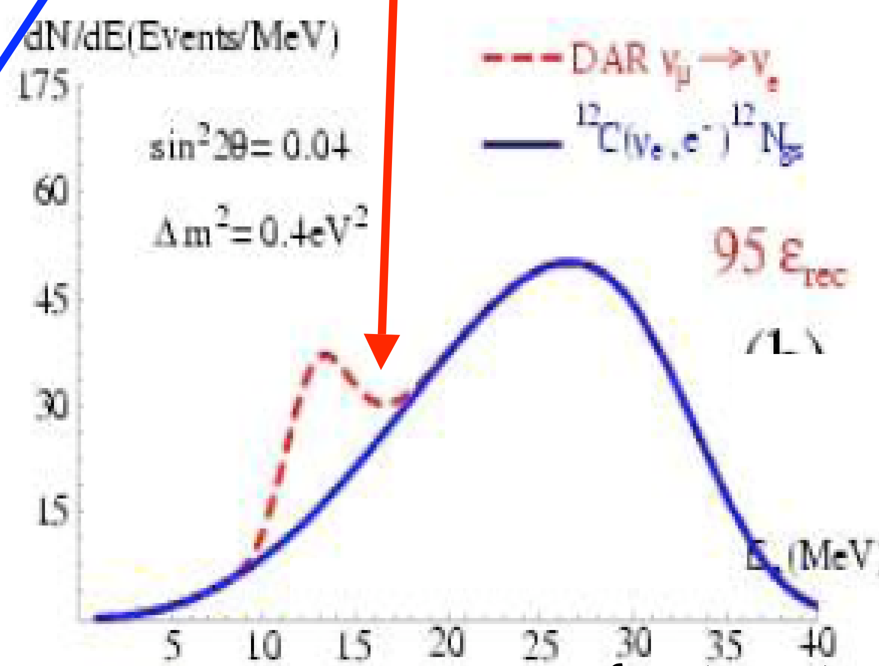
Neutrino Interactions @ SNS

- Appearance : $\nu_\mu \rightarrow \nu_e$
  - $\Rightarrow \nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$
  - $\Rightarrow {}^{12}N \rightarrow {}^{12}C + e^+ \, (\sim 8 \text{ MeV}) + \nu_e$

Intrinsic ν_e vs mono-energetic ν_e from ν_μ



E of e$^-$ (MeV)

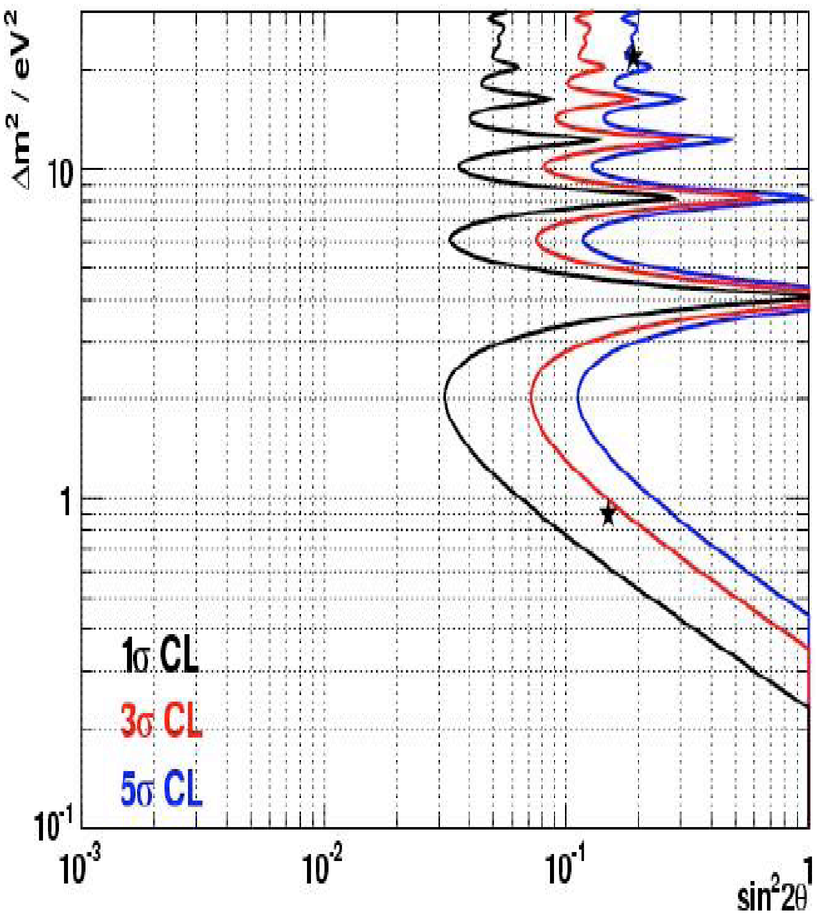


E of e$^-$ (MeV)

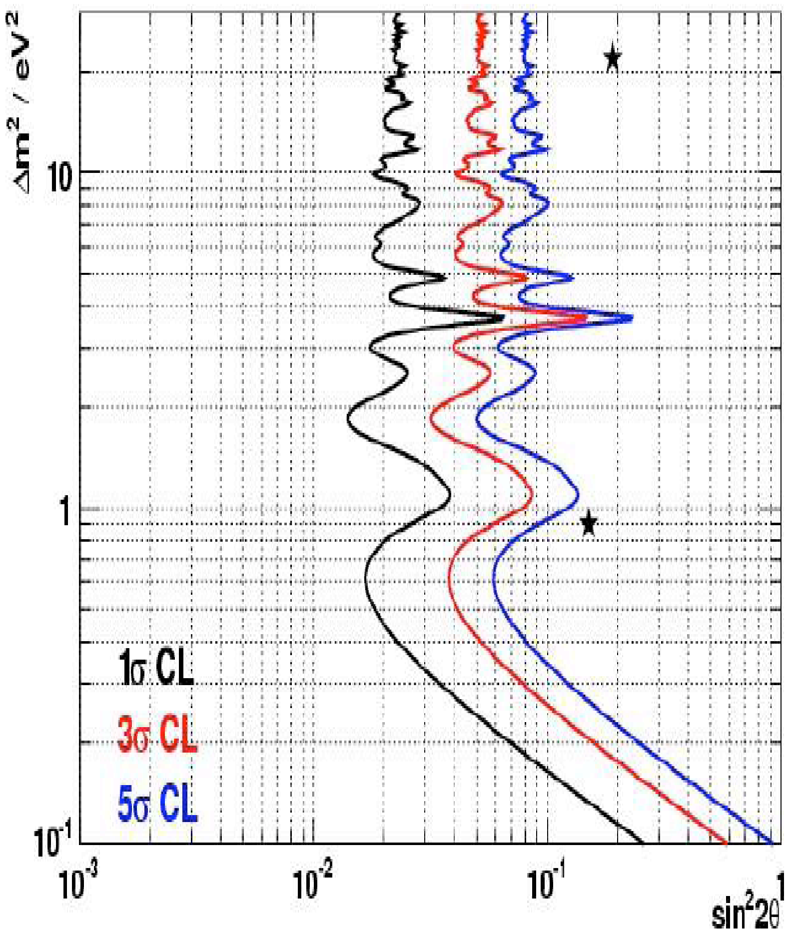
Sterile Neutrinos

- Sterile neutrinos = RH neutrinos, don't interact with other matter (LH = Weak)
- Use super-allowed NC interactions to search for oscillations between flavor states and sterile neutrinos
- Disappearance : $\nu_\mu \rightarrow \nu_e$
  - $\Rightarrow \nu_\mu + C \rightarrow \nu_\mu + C^*$
  - $\Rightarrow C^* \rightarrow C$ + 15.11 MeV photon
- One detector : look for deficit in ν_μ events
- Two detectors : compare overall ν_x event rates

Sterile Neutrinos



Near Detector only



Near + Far Detector

Mass Varying Neutrinos

- All positive oscillation signals occur in matter (K2K, KamLAND, LSND); no direct information on oscillation parameters in air/vacuum
- Impose relationship between nus + dark E through scalar field
- Scalar field couples to matter field = different osc parameters in vacuum & mediums
- MaVaNus + 1 Sterile nu = LSND yes, MB no!
- Require a path to detector which can be vacated/filled with dirt to test
  - ⇒ Barger, Marfalia, Whisnant. Phys. Rev. D 73, 013005 (2006)
  - ⇒ Schwetz, Winter. Phys. Lett. B633, 557-562 (2006)

Lorentz Violation

- LSND, Atm, Solar oscillations explained by small Lorentz violation
- Size of violation consistent with size of effects emerging from underlying unified theory at Planck scale
  - ⇒ Kostelecky, Mewes. hep-ph/0406255 (2004)
- Oscillations depend on direction of ν propagation
- Don't need to introduce neutrino mass!
- Look for sidereal variations in oscillation probability

CP/CPT Violation

- CPT violation (or CP + sterile neutrinos) allows different mixing for ν, anti-ν
- Possible explaination for positive LSND, null MiniBooNE
- Compare ν, anti-ν measured oscillation probabilities

$$\Rightarrow \mathrm{CP} : \nu_\mu \rightarrow \nu_e \neq \overline{\nu_\mu} \rightarrow \overline{\nu_e}$$

$$\Rightarrow \mathrm{CPT} : \nu_\mu \rightarrow \nu_e \neq \overline{\nu_e} \rightarrow \overline{\nu_\mu}$$ can't do at SNS!

$$\Rightarrow \mathrm{CPT} : \nu_\mu \rightarrow X \neq \overline{\nu_\mu} \rightarrow X$$

Why the SNS?

Confirm LSND

Inconclusive

Reject LSND

Looking for new physics

Need much higher statistics

Need to perform analysis with anti-neutrinos to completely rule out LSND

Precise, well-defined neutrino/anti-neutrino beam with very high statistics and low backgrounds

Why the SNS?

1. Tight beam window
   - ⇒ Small cosmic background
   - ⇒ 72% pure ν_μ sample
2. Decay-at-rest neutrino source
   - ⇒ extremely well defined flux and energy
   - ⇒ $Hg^+ + \pi^-$ = virtually no intrinsic neutrino backgrounds
3. High statistics
   - ⇒ ~2.2 x 10^{23} protons on target / year
   - ⇒ ~2.8 x 10^{22} neutrinos / year

Why the SNS?

- When FNAL completes running in 2010 we will still need to learn more
- SNS : better defined E spectrum to allow precise measurements
- SNS : simultaneous measurements in neutrino, anti-nu modes
- SNS : different systematics to LSND, MB
  - ⇒Second cross check of LSND
- SNS : can perform beyond the standard model searches not open to MB

Summary

- SNS is about to become the best neutrino based facility in the US
- DOE proposal for 2 near detectors awaiting funding
- LANL white paper produced for far detector
- Waiting on MiniBooNE result to go forward with a proposal
- Regardless of the outcome of MiniBooNE, the future of *precision* neutrino measurements in the US lies at the SNS!

Backup Slides

Extra Dimensions

- Extra-D theories confine SM particles to a brane
- Sterile neutrinos can travel off of the brane
- Fluctations in the brane increase the path-length of active neutrinos relative to sterile neutrinos
- How can we test this @ SNS? Maybe remove this slide